

# Low temperature broken symmetry phases of spiral antiferromagnets

Luca Capriotti<sup>1,2</sup> and Subir Sachdev<sup>3</sup>

<sup>1</sup>Credit Suisse First Boston (Europe) Ltd., One Cabot Square, London E14 4QJ, United Kingdom

<sup>2</sup>Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106-4030

<sup>3</sup>Department of Physics, Yale University, P.O. Box 208120, New Haven, CT 06520-8120

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We study Heisenberg antiferromagnets with nearest- ( $J_1$ ) and third- ( $J_3$ ) neighbor exchange on the square lattice. In the limit of spin  $S \rightarrow \infty$ , there is a zero temperature ( $T$ ) Lifshitz point at  $J_3 = \frac{1}{4}J_1$ , with long-range spiral spin order at  $T = 0$  for  $J_3 > \frac{1}{4}J_1$ . We present classical Monte Carlo simulations and a theory for  $T > 0$  crossovers near the Lifshitz point: spin rotation symmetry is restored at any  $T > 0$ , but there is a broken lattice reflection symmetry for  $0 \leq T < T_c \sim (J_3 - \frac{1}{4}J_1)S^2$ . The transition at  $T = T_c$  is consistent with Ising universality. We also discuss the quantum phase diagram for finite  $S$ .

Frustrated antiferromagnets have recently attracted much interest in connection with the possibility of stabilizing unconventional low temperature ( $T$ ) phases, possibly falling outside the known paradigms of condensed matter physics [1]. In this respect, the most interesting systems are those where the combined effect of frustration and quantum fluctuations is strong enough to prevent the onset of magnetic ordering, thus stabilizing ‘exotic’ quantum disordered ground states [2]. A very promising candidate for such a *spin-liquid* phase has been found in the two-dimensional  $J_1-J_3$  model defined by the following Hamiltonian

$$\hat{H} = J_1 \sum_{\langle i,j \rangle} \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j + J_3 \sum_{\langle\langle i,j \rangle\rangle} \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j , \quad (1)$$

where,  $\hat{\mathbf{S}}_i$  are spin- $S$  operators on a square lattice and  $J_1, J_3 \geq 0$  are the nearest- and third- neighbor antiferromagnetic couplings along the two coordinate axes. For this model, early large  $N$  computations, [3] and recent large scale Density Matrix Renormalization Group (DMRG) calculations for  $S = 1/2$  [4] have suggested the existence of a gapped spin liquid state with exponentially decaying spin correlations and no broken translation symmetry in the regime of strong frustration ( $J_3/J_1 \simeq 0.5$ ).

This paper will describe properties of the above model for large  $S$ , and discuss consequences for general  $S$ . Our results, obtained by classical Monte Carlo simulations and a theory described below, are summarized in Fig 1 for the limit  $S \rightarrow \infty$ . There is a  $T = 0$  state with long-range spiral spin order for  $J_3 > \frac{1}{4}J_1$ . We establish that at  $0 < T < T_c \sim (J_3 - \frac{1}{4}J_1)S^2$  above this state there is a phase with broken discrete symmetry of lattice reflections about the  $x$  and  $y$  axes, while spin rotation invariance is preserved. This phase has ‘Ising nematic’ order. We present strong numerical evidence that the transition at  $T_c$  is indeed in the Ising universality class. Such Ising nematic order was originally proposed in Ref. [3] for  $S = 1/2$  in a  $T = 0$  spin liquid phase described by a  $Z_2$  gauge theory [6]. Thus the same Ising nematic order

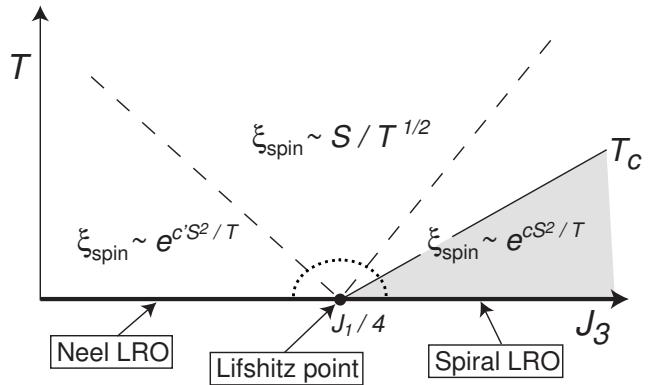


FIG. 1: Phase diagram of  $\hat{H}$  in the limit  $S \rightarrow \infty$ . The shaded region has a broken symmetry of lattice reflections about the  $x$  and  $y$  axes, leading to Ising nematic order. The Ising transition is at the temperature  $T_c \sim (J_3 - \frac{1}{4}J_1)S^2$ . The spin correlation length,  $\xi_{\text{spin}}$ , is finite for all  $T > 0$ , with the  $T$  dependencies as shown, with  $c/2 = c' = 8\pi|J_3 - \frac{1}{4}J_1|$ ; the crossovers between the different behaviors of  $\xi_{\text{spin}}$  are at the dashed lines at  $T \sim |J_3 - \frac{1}{4}J_1|S^2$ . Spin rotation symmetry is broken only at  $T = 0$  where  $\xi_{\text{spin}} = \infty$ . There is no Lifshitz point at finite  $S$  because it is pre-empted [5] by quantum effects within the dotted semi-circle: here there is a  $T = 0$  spin gap  $\Delta \sim S \exp(-\tilde{\alpha}S)$  and spin rotation symmetry is preserved. This semicircular region extends over  $T \sim |J_3 - \frac{1}{4}J_1|S \sim \Delta$ . Further details on the physics within this region appear at the end of the paper.

can appear when spiral spin order is destroyed either by thermal fluctuations (as in the present paper: see Fig 1) or by quantum fluctuations (as in Ref. [3]). Our large  $S$  results are therefore consonant with the possibility of a spin liquid phase at  $S = 1/2$  as described in Ref. [3, 4]; we will discuss the quantum finite  $S$  phase diagram further towards the end of the paper. We also suggest that discrete lattice symmetries may play a role near other quantum critical points with spiral order [7].

Broken discrete symmetries have also been discussed [8, 9] in the context of the  $J_1-J_2$  model, with first- and second-neighbor couplings on the square lattice. However this model has only collinear, commensurate spin

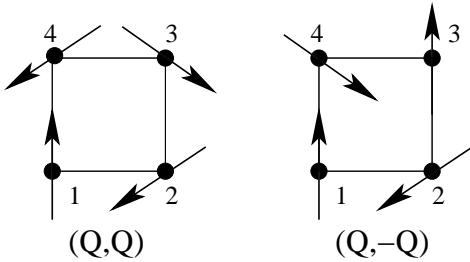


FIG. 2: The two different minimum energy configurations with magnetic wave vectors  $\vec{Q} = (Q, Q)$  and  $\vec{Q}^* = (Q, -Q)$  with  $Q = 2\pi/3$ , corresponding to  $J_3/J_1 = 0.5$ .

correlations, and this makes both the classical and quantum theory quite different from that considered here. As will become clear below, the spiral order and associated Lifshitz point, play a central role in the structure of our theory and in the  $T$  dependence of observables.

We begin by recalling [10] the ground states of  $\mathcal{H}$  at  $S = \infty$ . There is conventional Néel order with magnetic wavevector  $\vec{Q} = (\pi, \pi)$  for  $J_3/J_1 \leq \frac{1}{4}$ . For  $J_3/J_1 > \frac{1}{4}$  the ground state has planar incommensurate antiferromagnetic order, with a pitch vector depending on the frustration ratio. More precisely, the magnetic ordering can be described by a wavevector  $\vec{Q} = (Q, Q)$  with  $Q$  decreasing from  $\pi$  as  $J_3/J_1 > \frac{1}{4}$  and approaching  $Q = \pi/2$  monotonically for  $J_3/J_1 \rightarrow \infty$ ; at  $J_3 = \infty$  we obtain four decoupled Néel lattices. The spiral order is in general incommensurate for  $\frac{1}{4} < J_3/J_1 < \infty$ , with the exclusion of  $J_3/J_1 = 0.5$  where  $Q = 2\pi/3$ , corresponding to an angle of  $120^\circ$  between spins (See Fig. 2). Interestingly, for each spiral state with  $\vec{Q} = (Q, Q)$  there is an energetically equivalent configuration with  $\vec{Q}^* = (-Q, Q)$ , which is distinct from the first one for  $Q \neq \pi$ . This state cannot be obtained from the one with wavevector  $\vec{Q}$  by a global rotation of all the spins. Instead, the two configurations are connected to each other by a global rotation combined with a reflection about the  $x$  or  $y$  axes, so that the global symmetry of the classical ground state is  $O(3) \times Z_2$ , with an additional two-fold degeneracy beyond that of the Néel case.

One of the main claims in Fig 1 is that the broken  $Z_2$  symmetry survives for a finite range of  $T > 0$ , while continuous  $O(3)$  symmetry is immediately restored at any non-zero  $T$ , as required by the Mermin-Wagner theorem [11]. We established this by extensive Monte Carlo simulation using a combination of Metropolis and over-relaxed algorithm for periodic clusters of size up to  $M = 120 \times 120$ , and for several values of  $J_3/J_1$  between 0.25 and 4. Indeed, the presence of a finite  $T$  phase transition is clearly indicated by a sharp peak of the specific heat which is illustrated in Fig. 3. [12] This sharp feature is to be contrasted to the broad maximum displayed by the same quantity for  $J_3/J_1 < \frac{1}{4}$ , i.e., when the classical ground-state displays ordinary Néel order. In particular,

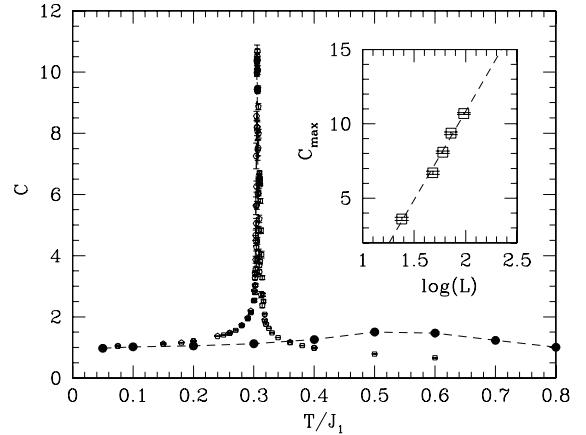


FIG. 3:  $T$  dependence of the specific heat for  $J_3/J_1 = 0.5$ . Different symbols refer to different clusters with liner size between  $L = 24$  and  $L = 120$ . Data for  $J_3/J_1 = 0.1$  are shown for comparison (full dots and dashed line). Inset: size-scaling of the maximum of the specific heat.

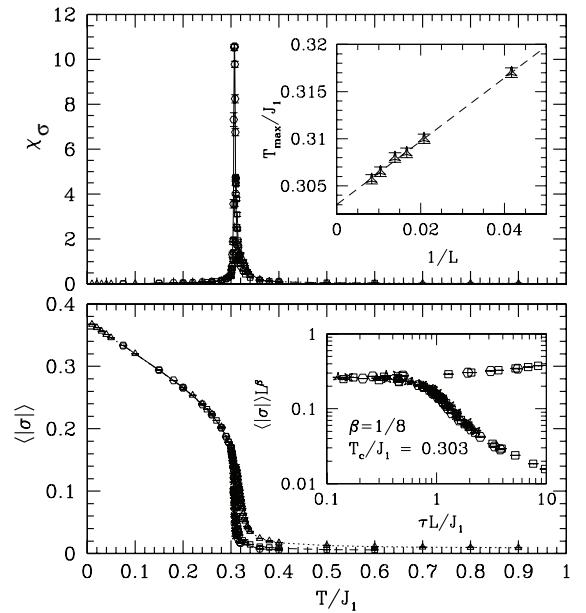


FIG. 4: Bottom:  $T$  dependence of the order parameter,  $\sigma$ , (see Eq. (2)) for different cluster sizes and  $J_3/J_1 = 0.5$ . The inset shows the data collapse according to the scaling hypothesis with Ising exponents  $\beta = 1/8$  and  $\nu = 1$ , and  $T_c = 0.303$ . Top: Temperature dependence of the susceptibility of  $\sigma$  for  $J_3/J_1 = 0.5$ . The inset shows the size scaling of the maximum of the susceptibility.

the maximum of the specific heat is consistent with a logarithmic dependence on system size (see the inset of Fig. 3) corresponding to a critical exponent  $\alpha = 0$ , in agreement with Ising universality.

This critical behavior can be directly related to the broken lattice reflection symmetry by studying an appropriate Ising nematic order parameter. From the symmetries of Fig 2, we deduce that the order parameter is

$\sigma = 1/M (\sum_a \sigma_a)$  with

$$\sigma_a = \left( \hat{\mathbf{S}}_1 \cdot \hat{\mathbf{S}}_3 - \hat{\mathbf{S}}_2 \cdot \hat{\mathbf{S}}_4 \right)_a , \quad (2)$$

where  $a$  labels each plaquette of the square lattice and  $(1, 2, 3, 4)$  are its corners. The variables  $\sigma_a$  are identically zero for a Néel antiferromagnet, while they assume opposite signs on the two degenerate ground states in the spiral phase. In a phase with all the symmetries of the Hamiltonian,  $\langle \hat{\mathbf{S}}_1 \cdot \hat{\mathbf{S}}_3 \rangle = \langle \hat{\mathbf{S}}_2 \cdot \hat{\mathbf{S}}_4 \rangle$  so that  $\langle \sigma_a \rangle$  vanishes; a phase with Ising nematic order is signaled by a  $\langle \sigma_a \rangle \neq 0$ .

Indeed, as clearly shown in Fig. 4 (lower panel), the critical behavior signaled by the divergence of the specific heat corresponds to a continuous phase transition between a low  $T$  phase with a finite value of  $\sigma$  in the thermodynamic limit, and a homogeneous high  $T$  phase. Such a transition is also clearly evidenced by a sharp divergence of the susceptibility of the Ising nematic order parameter defined by  $\chi_\sigma = (M/T) (\langle \sigma^2 \rangle - \langle |\sigma| \rangle^2)$  (see Fig. 4, upper panel), and also by the  $T$  dependence of Binder's fourth cumulant  $U_4 = 1 - \langle \sigma^4 \rangle / 3\langle \sigma^2 \rangle^2$  (not shown).

The critical exponent  $\nu$  can be easily estimated from the size dependence of the  $T$  corresponding to the maximum of the susceptibility, which is expected to scale as  $T_{max}(L) = T_c + aL^{-1/\nu}$ , where  $T_c$  is the thermodynamic critical temperature. As shown in Fig. 4 (upper inset), no sizable deviation from the Ising exponent  $\nu = 1$  is observed. The exponent  $\beta$  is also in agreement with the Ising universality class. This can be extracted by performing a size scaling analysis of the order parameter around the critical  $T$ . In fact, according to the scaling hypothesis, close to  $T_c$ ,  $|\sigma| = L^{-\beta/\nu} f(x)$ , where  $f(x)$  is the scaling function, and  $x = \tau L^{1/\nu}$  with  $\tau = |T - T_c|$ . We have therefore plotted  $\sigma L^{\beta/\nu}$  as a function of  $x$ , using the value of the critical temperature  $T_c = 0.303(1)$  that can be estimated from the position of the maximum of the susceptibility (Fig. 4, upper inset), and the behavior of the Binder's cumulant. As shown in Fig. 4 (lower inset), an excellent collapse of the data for different lattice sizes on the same curve is obtained for  $\beta/\nu = 1/8$ .

We have repeated a similar analysis for several values of  $J_3/J_1$  and the complete phase diagram is shown in Fig. 5, where we have plotted  $T_c$  vs  $J_3/J_1$ . We find that  $T_c$  vanishes linearly for  $J_3/J_1 \rightarrow 1/4$ ; a theory for this behavior will now be presented.

Near the classical Lifshitz point, we can model quantum and thermal fluctuations by a continuum unit vector field  $\mathbf{n}(r, \tau)$ , where  $r = (x, y)$  is spatial co-ordinate,  $\tau$  is imaginary time, and  $\mathbf{n}^2 = 1$  at all  $r, \tau$ . This field is proportional the Néel order parameter with  $\hat{\mathbf{S}}_j \propto (-1)^{x_j+y_j} \mathbf{n}(r_j, \tau)$ . Spiral order will therefore appear as sinusoidal dependence of  $\mathbf{n}$  on  $r$ . The action for  $\mathbf{n}$  is the conventional O(3) non-linear sigma model, expanded to include quartic gradient terms ( $\hbar = k_B =$

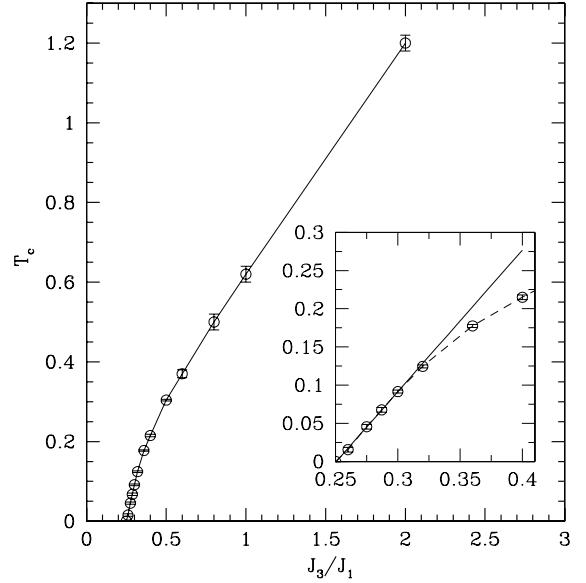


FIG. 5: Critical temperature as a function of the frustration ratio  $J_3/J_1$ .

lattice spacing = 1):  $\mathcal{S}_n = \int_0^{1/T} d\tau \int d^2r \mathcal{L}_n$  with

$$\begin{aligned} \mathcal{L}_n = & \frac{\chi_\perp}{2} (\partial_\tau \mathbf{n})^2 + \frac{\rho}{2} [(\partial_x \mathbf{n})^2 + (\partial_y \mathbf{n})^2] \\ & + \frac{\zeta_1}{2} [(\partial_x^2 \mathbf{n})^2 + (\partial_y^2 \mathbf{n})^2] + \zeta_2 \partial_x^2 \mathbf{n} \cdot \partial_y^2 \mathbf{n} \\ & + \lambda_1 [(\partial_x \mathbf{n} \cdot \partial_x \mathbf{n})^2 + (\partial_y \mathbf{n} \cdot \partial_y \mathbf{n})^2] + \lambda_2 (\partial_x \mathbf{n} \cdot \partial_y \mathbf{n})^2 + \dots \end{aligned} \quad (3)$$

where the ellipses denote a finite number of additional  $\lambda_i$  couplings involving 4 powers of  $\mathbf{n}$  and 4 spatial derivatives invariant under spin rotations and lattice symmetries. In the limit  $S \rightarrow \infty$  we have  $\chi_\perp = 1/(8J_1)$ ,  $\rho = (J_1 - 4J_3)S^2$ ,  $\zeta_1 = (16J_3 - J_1)S^2/12$ ,  $\zeta_2 = 0$ , and all  $\lambda_i = 0$ . Notice that  $\rho$  crosses zero at the Lifshitz point and so can be regarded as the tuning parameter;  $\rho = 0$  generally locates the Lifshitz point for when  $\rho < 0$  it is energetically advantageous to have a  $r$ -dependent spiral in  $\mathbf{n}$ .

A convenient analysis of the properties of  $\mathcal{S}_n$  is provided by a direct generalization of the  $1/N$  expansion of Ref. [13]. The results quoted in Fig 1 and its caption were obtained from the  $N = \infty$  saddle point equation, and (apart from certain pre-exponential factors) all functional forms are exact. The saddle point implements the constraint  $\mathbf{n}^2 = 1$  and takes the form

$$3T \sum_{\omega_n} \int \frac{d^2k}{4\pi^2} \chi_n(k, \omega_n) = 1 , \quad (4)$$

where  $k$  is a wavevector,  $\omega_n$  is a Matsubara frequency, and  $\chi_n$  is the dynamic staggered spin susceptibility with

$$\begin{aligned} \chi_n(k, \omega_n) = & \left( m^2 + \chi_\perp \omega_n^2 + \rho(k_x^2 + k_y^2) \right. \\ & \left. + \zeta_1(k_x^4 + k_y^4) + 2\zeta_2 k_x^2 k_y^2 \right)^{-1} . \end{aligned} \quad (5)$$

The parameter  $m$  is determined by solving Eq. (4).

In the classical limit,  $S \rightarrow \infty$ , we need only retain the  $\omega_n = 0$  term in Eq. (4) [14]. A solution for  $m$  exists for all

$T > 0$ , and leads to the crossovers in the spin correlation length  $\xi_{\text{spin}}$  shown in Fig 1. The value of  $\xi_{\text{spin}}$ , and the pitch of the spiral order  $\sim \sqrt{-\rho}$ , as  $T \rightarrow 0$  are obtained from the spatial Fourier transform of  $\chi_{\mathbf{n}}(k, 0)$ .

To investigate the Ising nematic order, we need to study correlations of the order parameter  $\sigma(r, \tau)$  which we define by a gradient expansion of Eq. (2)

$$\sigma = \mathbf{n} \cdot \partial_x \partial_y \mathbf{n} - \partial_x \mathbf{n} \cdot \partial_y \mathbf{n}. \quad (6)$$

The Ising susceptibility,  $\chi_\sigma$  is then  $\chi_\sigma = \int_0^{1/T} d\tau \int d^2r \langle \sigma(r, \tau) \sigma(0, 0) \rangle$ .

In the classical limit,  $S \rightarrow \infty$ , important exact properties of  $\chi_\sigma$  follow from the ultraviolet finiteness of the two-dimensional field theory with Boltzmann weight  $\exp(-(1/T) \int d^2r \mathcal{L}_{\mathbf{n}})$  and  $\mathbf{n}$  independent of  $\tau$ . Under a length rescaling analysis of this theory in which the  $\zeta_i$  and  $\lambda_i$  are fixed, we see that both  $T$  and  $\rho$  scale as inverse length squared. These scaling dimensions establish that in the classical limit

$$\xi_{\text{spin}} = \sqrt{\zeta_1/T} \Phi_1(\rho/T) ; \quad \chi_\sigma = \zeta_1^{-1} \Phi_2(\rho/T), \quad (7)$$

where  $\Phi_i$  are cut-off independent scaling function which depends only on ratios of the  $\zeta_i$  and  $\lambda_i$ . The Ising phase transition is associated with a divergence of  $\Phi_2$  at some negative argument of order unity, and Eq. (7) then implies the  $T_c \sim -\rho$  dependence shown in Fig 1, and verified numerically in Fig 5. We can also compute  $\chi_\sigma$  (including the quantum  $\omega_n \neq 0$  modes) in the large  $N$  limit and obtain

$$\chi_\sigma = 24T \sum_{\omega_n} \int \frac{d^2k}{4\pi^2} k_x^2 k_y^2 \chi_{\mathbf{n}}^2(k, \omega_n). \quad (8)$$

Using the results in Eq. (5), Eq. (8) predicts an exponential divergence in  $1/T$  as  $T \rightarrow 0$  for  $\rho < 0$ . This is, of course, an artifact of the large  $N$  limit, as our Monte Carlo studies clearly show that  $\chi_\sigma$  diverges with a power-law Ising exponent at a  $T_c > 0$ .

We turn now to a discussion of the quantum physics at finite  $S$ . A key feature again emerges from an analysis of Eqs. (4) and (5), while retaining the full frequency summation: the soft spin spectrum ( $\omega \sim k^2$ ) at the Lifshitz point implies that there cannot be long-range magnetic order over a finite regime of parameters for all finite  $S$  [5]. After evaluating the frequency integral at  $T = 0$ , a solution with  $m$  real exists for a range of values of  $|J_3 - \frac{1}{4}J_1|$  smaller than  $\sim e^{-\tilde{c}S}$ , implying there is a spin gap in this regime. We can reasonably expect that the Ising nematic order survives into at least a portion this spin gap phase, as it does at  $T > 0$ .

A more careful analysis of the spin gap phase requires consideration of Berry phases [1, 3], which are absent in  $\mathcal{L}_{\mathbf{n}}$ . Assuming second order quantum critical points, with increasing  $J_3$ , we first expect a spin gap state with valence bond solid (VBS) order and confined  $S = 1/2$

spinon excitations after leaving the collinear Néel state. Conversely, decreasing  $J_3$  from the spiral spin ordered phase, we expect a  $Z_2$  spin liquid with Ising nematic order and deconfined bosonic spinons [3, 6]. So quite remarkably, we expect the following sequence of 4 phases to appear *for all half-odd-integer spin S* with increasing  $J_3$ : Néel LRO–VBS– $Z_2$  spin liquid–spiral LRO. The 2 intermediate phases have a spin gap, and they appear in a window which is exponentially small in  $S$  for large  $S$ ; the latter 2 phases have Ising nematic order. Theories for the 3 quantum critical points between these 4 phases appear in Refs. [1, 15]. Of course, we cannot rule out the possibility that the some of these critical points and intermediate phases are pre-empted by a first order transition.

It is interesting to note that other  $Z_2$  spin liquids with fermionic  $S = 1/2$  spinons have been proposed [16], in which the ground state does not have Ising nematic order. Our present results naturally suggest a spin gap state with Ising nematic order, and mean field theories for such states have only been obtained with bosonic spinons [3]. Further studies of Ising nematic order in quantum spin models will therefore be valuable in resolving the nature of the spin liquid state.

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